Recent STAR Results on the Unpolarized Light Quark Flavor Structure at RHIC

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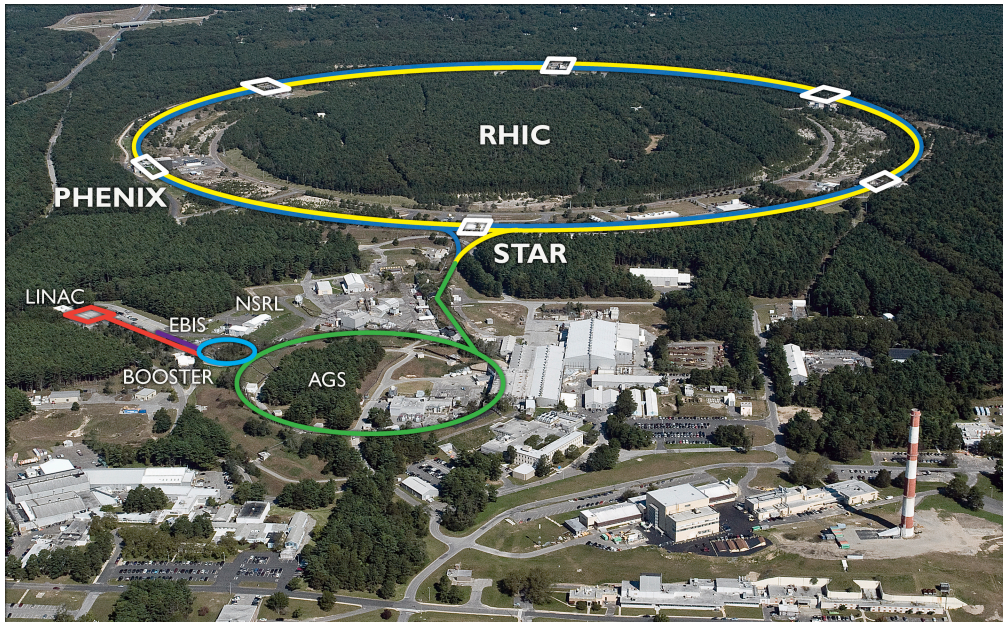
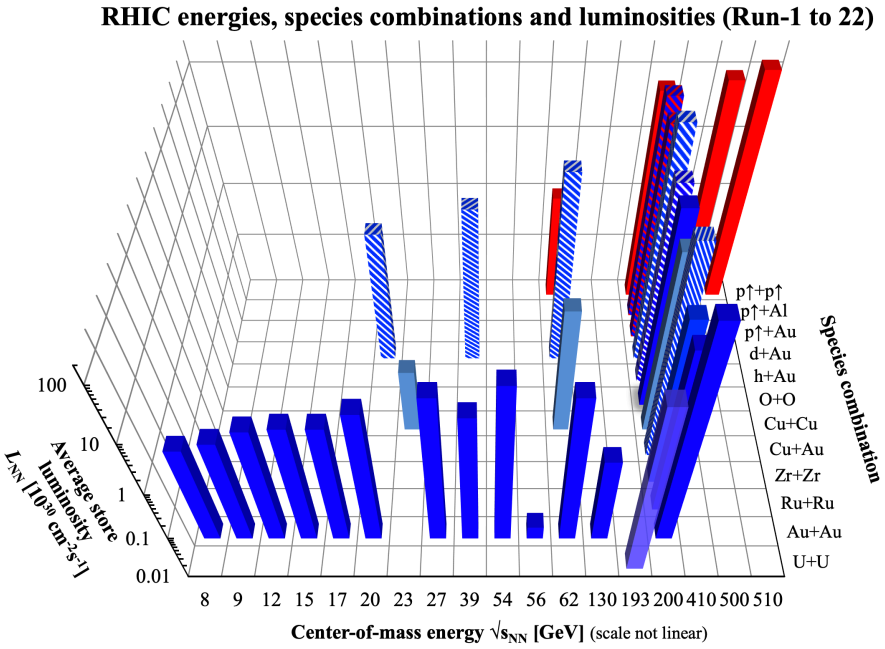
Temple Univ.

Relativistic Heavy Ion Collider





- RHIC continues to serve as the world's first and only polarized pp collider.
- Features pp collisions at $\sqrt{s} = 500/510\ GeV$ and $\sqrt{s} = 200\ GeV$.
- pA/AA collisions at $\sqrt{s_{NN}} = 10\sim200\ GeV$.

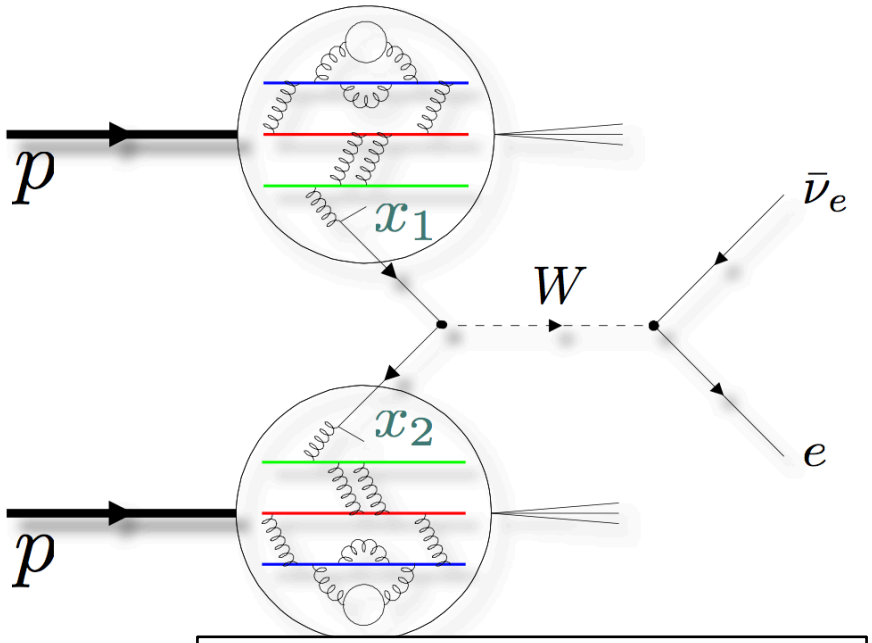
- At RHIC, protons can be polarized either:
  - Longitudinally (along the direction of the beam)
    - → Proton spin composition
  - Transversely (perpendicular to the beam)
    - → 3D image of the proton
  - Or can be unpolarized (if we choose not to look at the polarization)
    - → **Parton distribution functions**
    - → Non-linear gluon effects

Measurements of PDFs at RHIC

- Drell-Yan type measurements:

$$d\sigma \sim \sum_{1,2} \left[f_1(x_1)\bar{f}_2(x_2) + \bar{f}_1(x_1)f_2(x_2) \right] \otimes d\hat{\sigma}_{1,2}$$

  - Sensitive to both quark/anti-quarks in the proton.
  - Simple final state of charged leptons: No dependency on FFs.

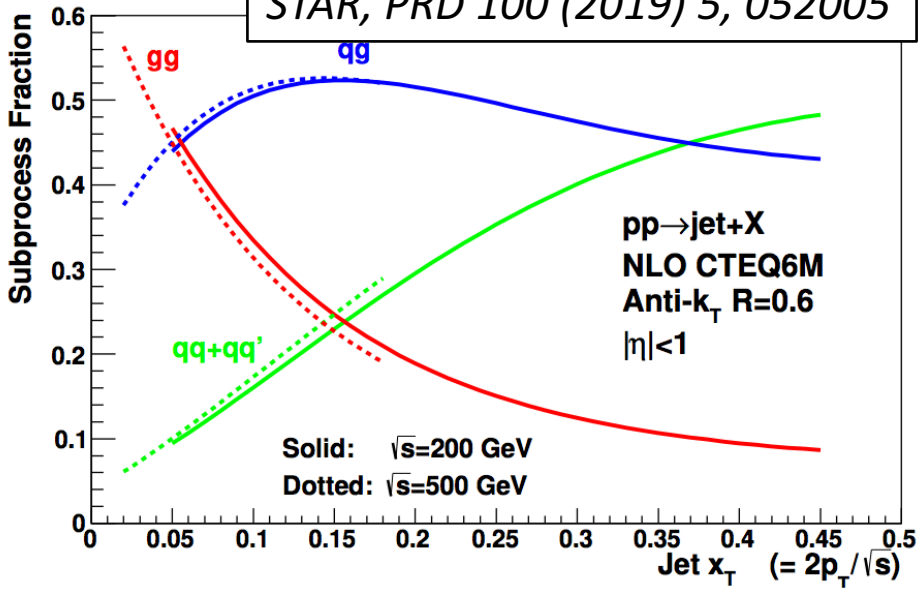


- Inclusive Jet measurements:

$$d\sigma \sim \sum_{1,2} f_1(x_1, Q_1^2) f_2(x_2, Q_2^2) \otimes d\hat{\sigma}_{1,2}$$

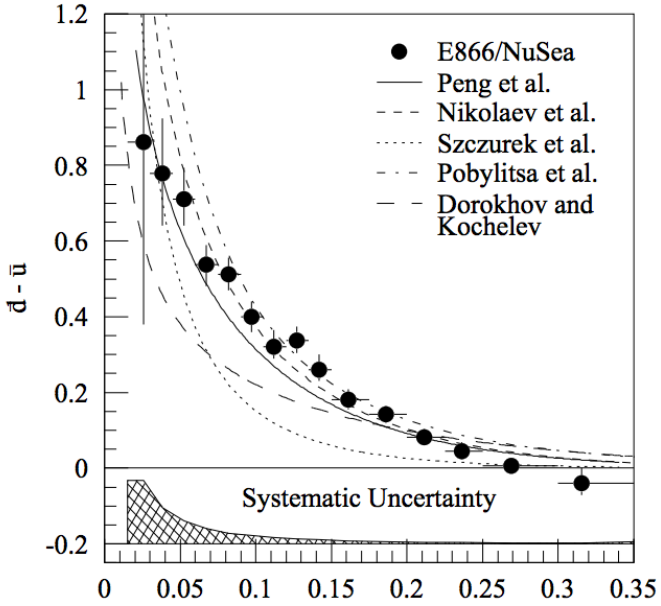
  - Jets in STAR kinematics sensitive to gluons in the proton.
  - Many jet studies have been already produced from STAR with polarized beams.
  - Different CoM energy / jet topology provide additional information of the initial state proton

STAR, PRD 100 (2019) 5, 052005

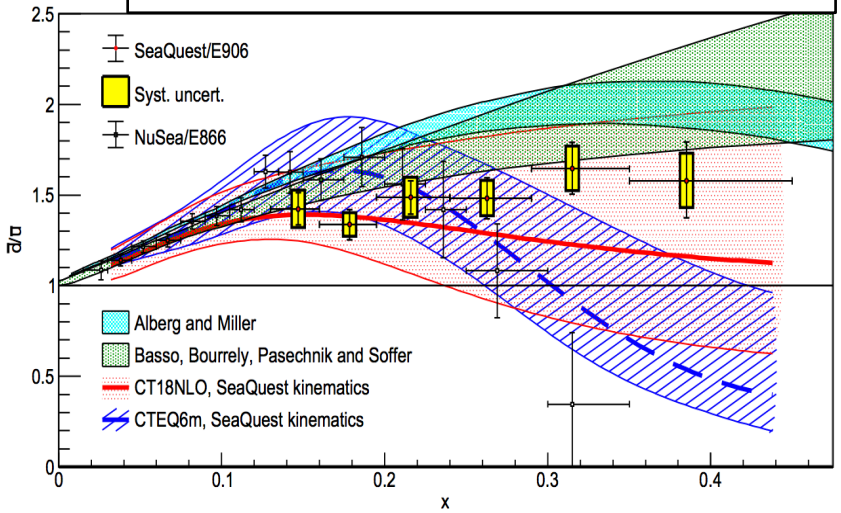


$\bar{d}/\bar{u}$ asymmetry

NuSea, Phys.Rev.D 64 (2001) 052002



SeaQuest, Nature 590 (2021) 7847, 561-565



- While the valence quark (d, u) structure of the proton is well determined, the anti-quark counter part $(\bar{d}, \bar{u})$ is much less constrained.
- Non-diminishing asymmetry between the anti-quarks in the proton sea $\bar{d}, \bar{u}$ is a purely non-perturbative phenomenon.
- The anti-quark ratio $\bar{d}/\bar{u}$ is typically measured in Drell-Yan type experiments with deuterons.
- Inconsistencies among these measurements have been found, especially in the proton momentum fraction range $x > 0.2$.
- W measurements at RHIC may provide some insight around the region of conflict.

W production in pp collisions

- $W^{\pm}$ cross sections at LO
  - $d\sigma^{W+} \propto u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)$
  - $d\sigma^{W-} \propto \bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_1)$

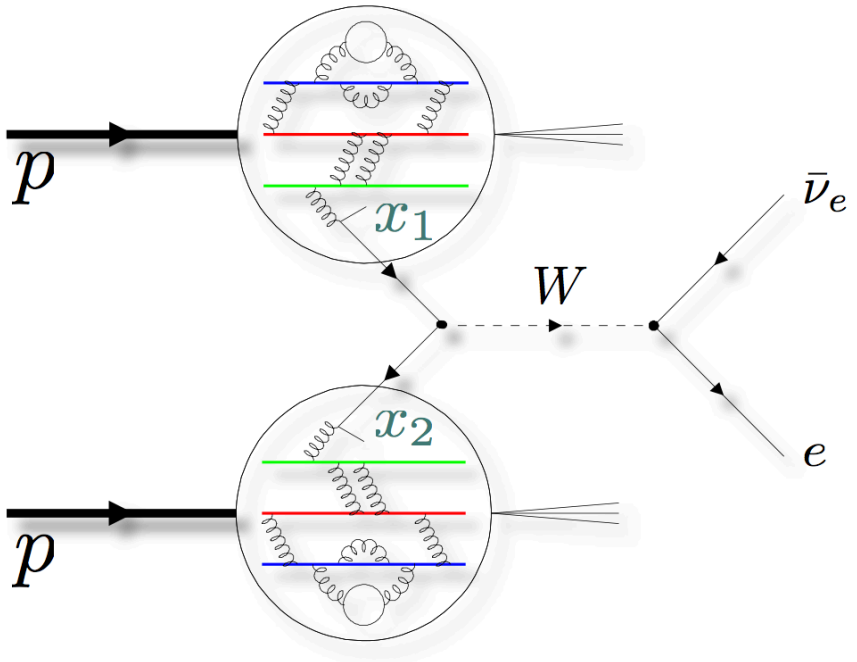
$$\rightarrow R_W = \frac{\sigma^{W+}}{\sigma^{W-}} \sim \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{\bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_2)}$$

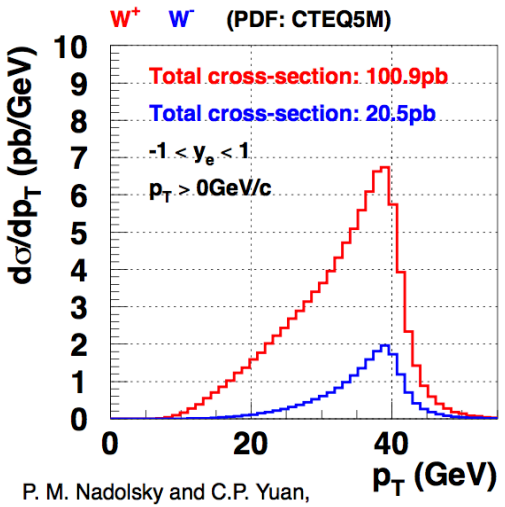
- At LO, momentum scale set by the W mass, $Q^2 \sim M_W^2$.
- Leptonic decay via $W \rightarrow e\nu$
  - $\frac{d\sigma(W^{\pm}\rightarrow e\nu)}{dp_{T,e}^2} \propto \frac{(1\pm\cos\theta)^2}{M_W \cos\theta}$
  - $p_{T,e} \sim \frac{M_W}{2}\sin\theta$

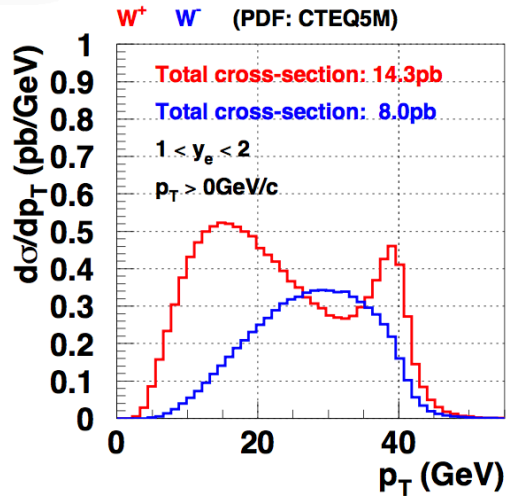
  → Jacobian peak at $p_{T,e} \sim M_W/2$
  - $y_e \sim y_W + \frac{\ln 1+\cos\theta}{\ln 1-\cos\theta}$

  → Charge discrimination as a function of y_e.

- Key features in experiment
  - High p_T electron.
  - Electron/Hadron discrimination needed.
  - Large imbalance in p_T in detector due to ν.



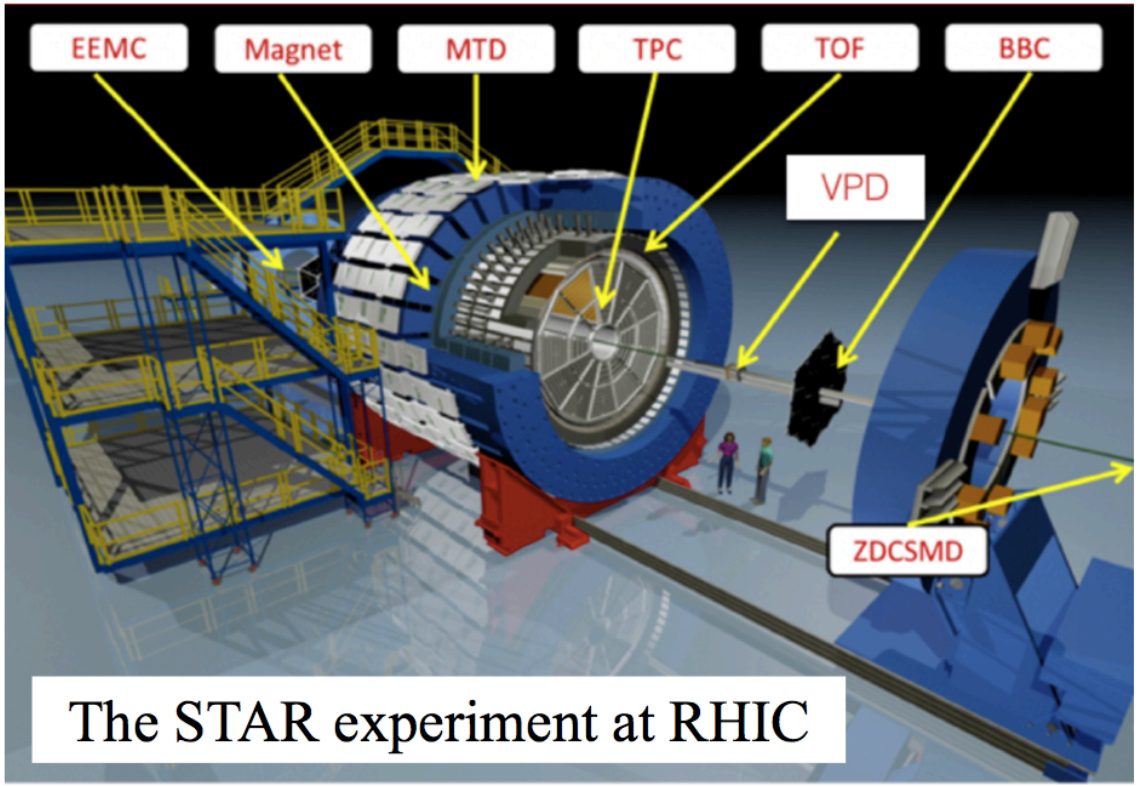




P. M. Nadolsky and C.P. Yuan, Nucl.Phys. B666 (2003) 31.

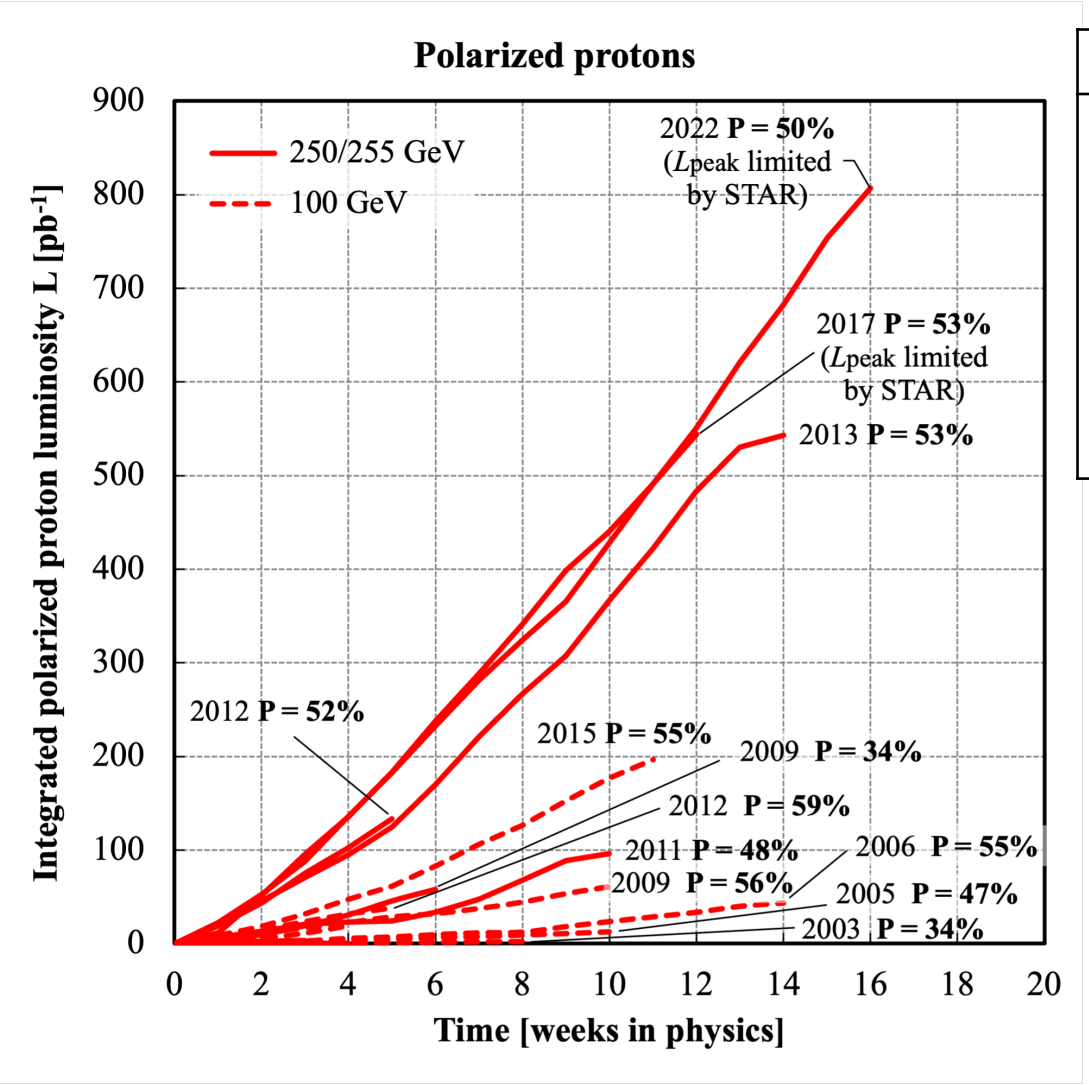
Solenoid Tracker At RHIC (STAR)

- For measurements of W bosons, it is important to achieve near 4π detector acceptance.
- Time Projection Chamber(TPC)
  - Acceptance of $|\eta| < 1.3$.
  - Provides tracking & PID.
- Electro-Magnetic Calorimenter
  - Barrel (BEMC): $|\eta| < 1$.
  - Endcap (EEMC): $1 < \eta < 2$.
  - Assists in electron/hadron discrimination.
  - Assists in electron charge discrimination.
- Luminosity monitoring & Vertexing
  - Beam-Beam Counter (BBC)
  - Zero Degree Counter (ZDC)
  - Vertex Position Detector (VPD)



- The W bosons detected in the combined TPC + BEMC (barrel region) arise from a kinematic region of $0.1 < x < 0.3$.
- EEMC provides coverage in the intermediate region $1 < \eta < 2$, extending the kinematic reach to $0.06 < x < 0.4$.

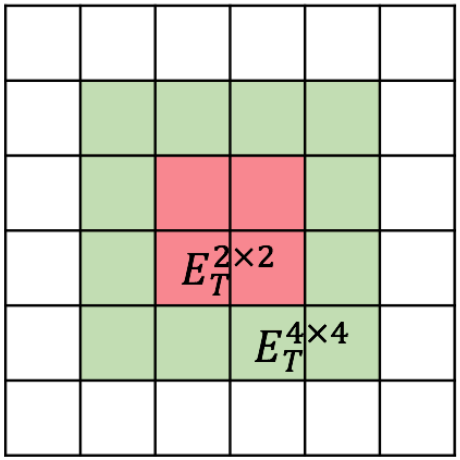
RHIC pp Run Overview



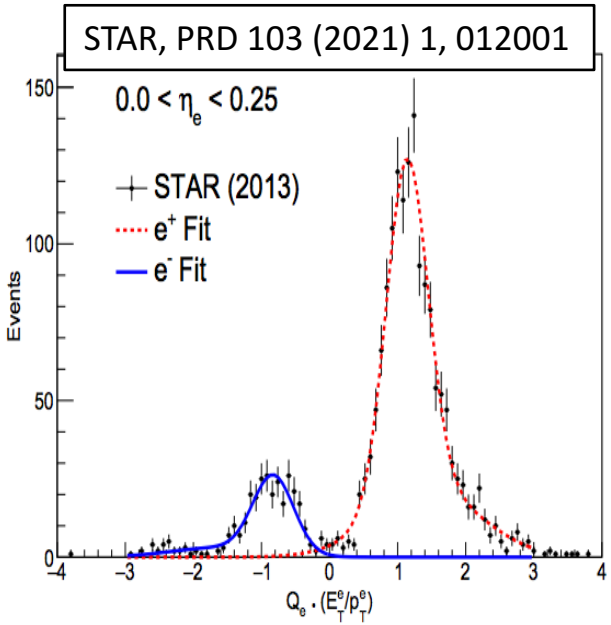
Run	$\sqrt{s}\ (GeV)$	$L\ (pb^{-1})$
2009	500	10
2011	500	25
2012	510	75
2013	510	250
2017	510	350
2022	510	400 (estimate)

- $L \sim 700 + 400\ pb^{-1}$ of pp collisions with sufficiently high $\sqrt{s}$ has been collected at STAR.
  - Initial measurement based on Run 2009 with $L \sim 10\ pb^{-1}$. (STAR, PRD 85 092010)
  - Follow up study with Run 2011-2013 with $L \sim 350\ pb^{-1}$ has been published. (STAR, PRD 103,012001)
  - Preliminary study based on Run 2017 with $L \sim 350\ pb^{-1}$.
  - New dataset with $L \sim 400\ pb^{-1}$.

W tagging in the barrel ($|\eta_e| < 1$)

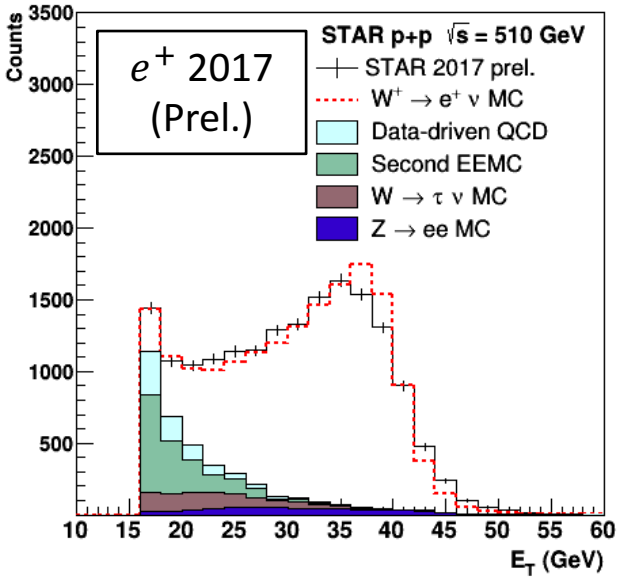


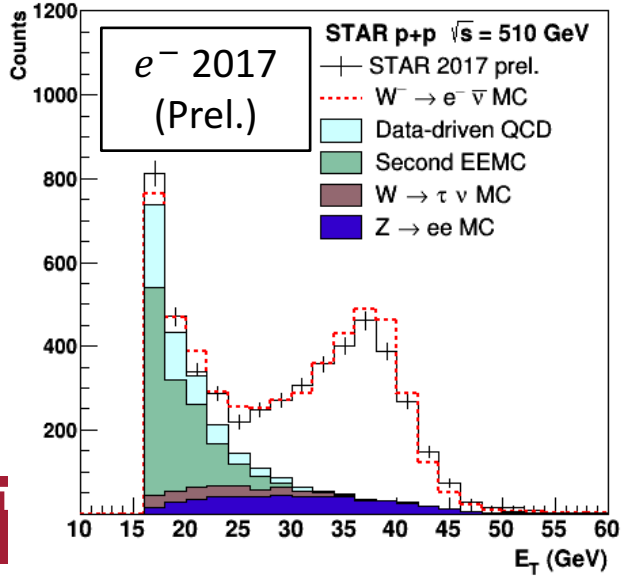
TPC track extrapolated to BEMC tower grid



- W bosons that undergo the leptonic decay process, $W \rightarrow e\nu$, are tagged.
- Imbalance in p_T due to the missing neutrino. High $\vec{p}_{T,bal}$ $(= \vec{p}_{T,e} + \Sigma\vec{p}_{T,recoil})$ events are selected.
- Unlike hadrons, electrons deposit their energy in a highly concentrated region in the EMC. This isolated electron energy deposit is quantified with $E_T^{2\times2}/E_T^{4\times4}$.
- Charge separation from TPC + EMC ($Q_e \times E_T/p_T$).
- Although not in this measurement, full W kinematics can be reconstructed.
  - Used for measurements of Sivers effect.

Backgrounds in the barrel

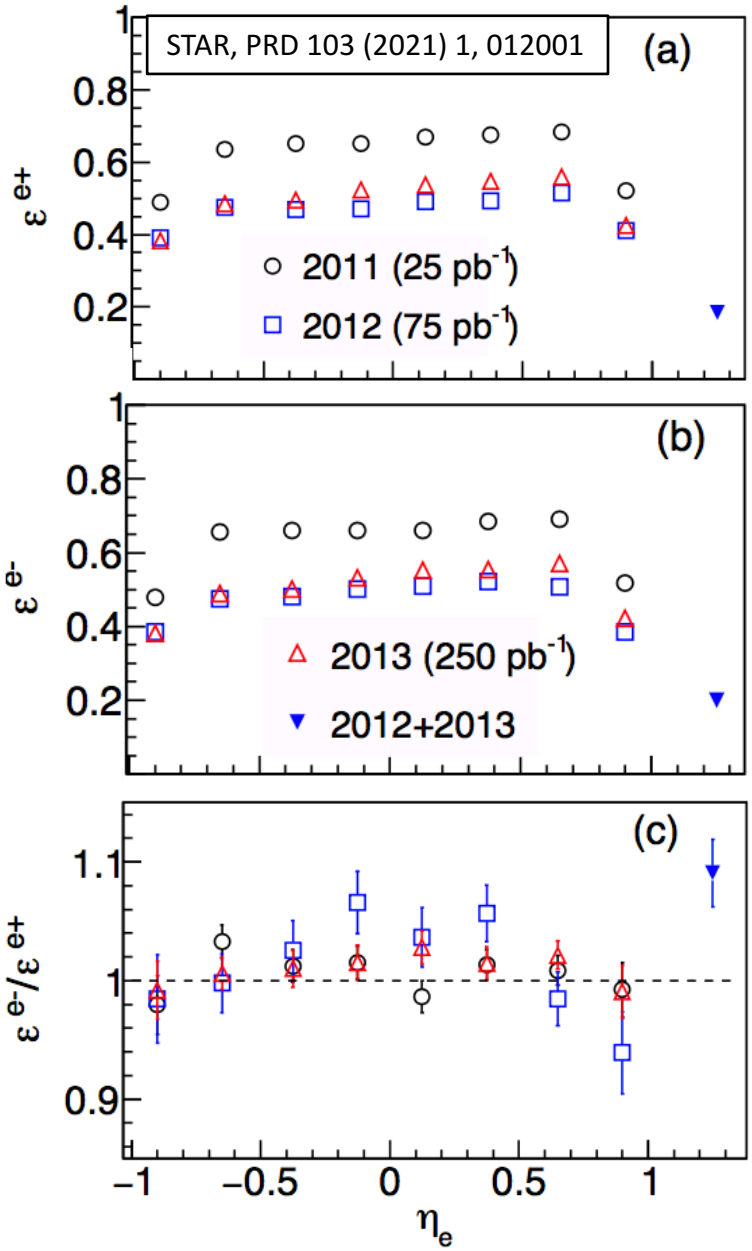




- Electroweak ($N_{Z\rightarrow ee}$, $N_{W\rightarrow \tau\nu}$)
  - Z decays with one unidentified electron
  - Leptonic decay of τ^W
  - Estimated with MC (Pythia)

- QCD background
  - Due to the limited acceptance and kinematic coverage, imbalance in p_T may appear in QCD events.
  - Two methods employed to estimate their contributions:
  - Second EEMC (N_{EEMC})
    - Accounts for missing backward coverage ($-2 < \eta < -1$)
    - Estimated by mirroring the effect of existing EEMC in the forward direction.
  - Data-driven QCD (N_{QCD})
    - Remaining background contribution that passes the selection process.
    - Distribution obtained by using events that do not pass the $p_{T,bal}$.

Efficiencies in the barrel



- In the W cross-section ratio measurement, the expression of the ratio reduces to:

$$\sigma_{W^+}/\sigma_{W^-} = \frac{N^+_{obs}}{\epsilon^+ \int Ldt} \Big/ \frac{N^-_{obs}}{\epsilon^- \int Ldt}$$

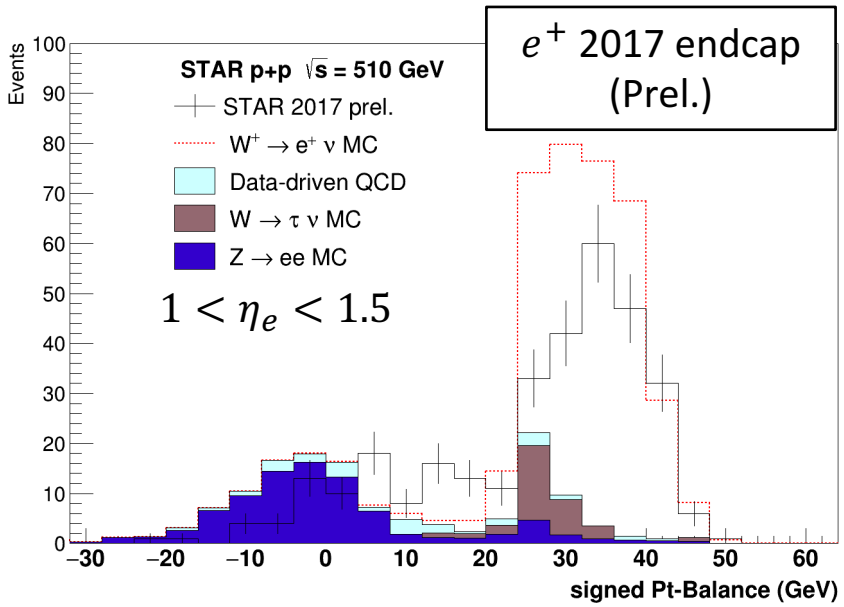
$$= \frac{\epsilon^-}{\epsilon^+} \cdot \frac{N^+_{sig} - N^+_{bg}}{N^-_{sig} - N^-_{bg}}$$

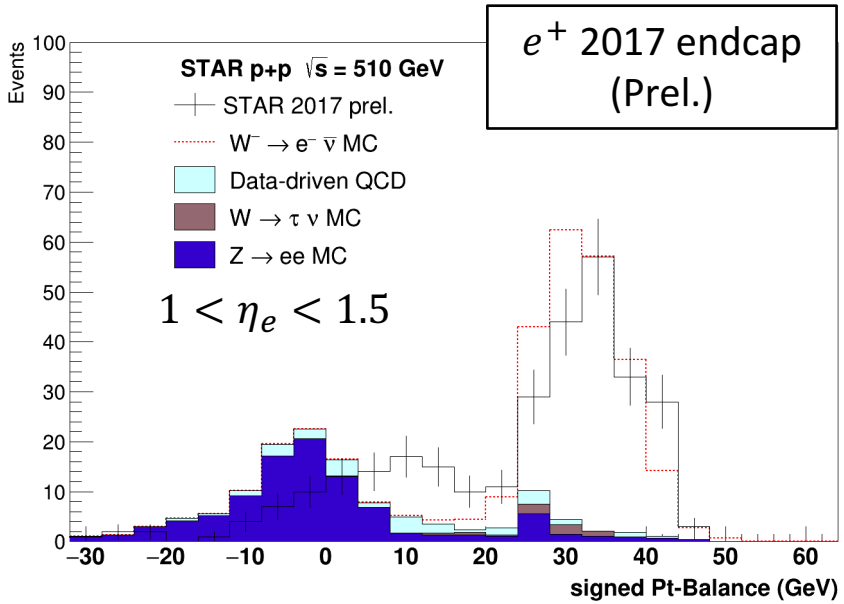
- where ϵ represents the product of the efficiencies of our selection process.

$$\epsilon = \epsilon_{trigger} \times \epsilon_{vertex} \times \epsilon_{tracking} \times \epsilon_{tagging}$$

- Lower efficiency in Run 2012 and 2013 (compared to Run 2011) due to higher material deposits.
- Higher tracking efficiency in 2013 than in 2012 due to improvements in tracking algorithm.
- MC study suggests that the efficiency ratio ϵ^-/ϵ^+ is consistent with unity and the deviation from unity is taken as a source of systematic uncertainty.

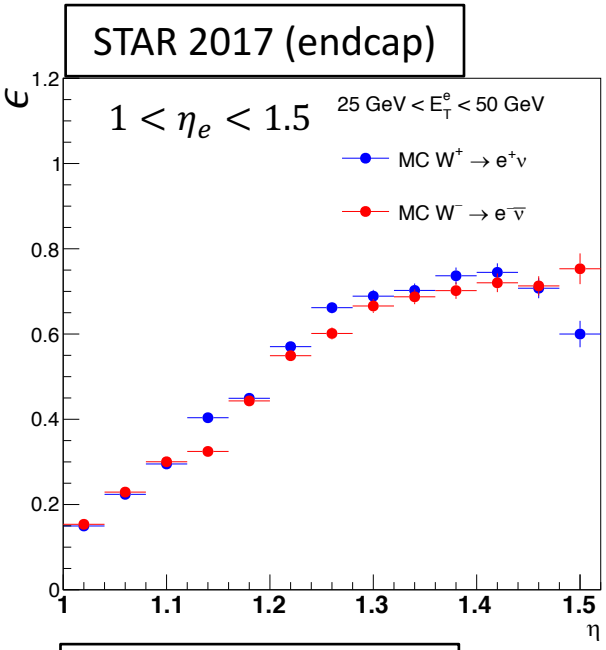
Endcap measurement

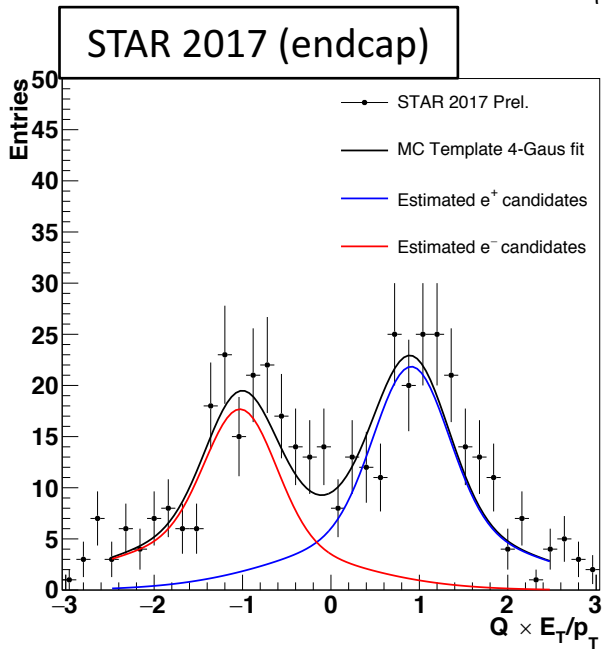




- W tagging method in the endcap region is similar to that for the barrel region.
  - Relaxed tracking requirements.
  - Employ EEMC and its subcomponents instead of BEMC.
- Background description also follows a similar procedure.
  - Simulations are used to estimate electroweak background.
  - Description of QCD background purely relies on data-driven method.
- Mismatch in signed-$p_{T,bal} < 20\ GeV$ due to suboptimal QCD background description.
  - Effect taken as a systematic uncertainty.
  - To be improved in the final measurement.

Endcap corrections

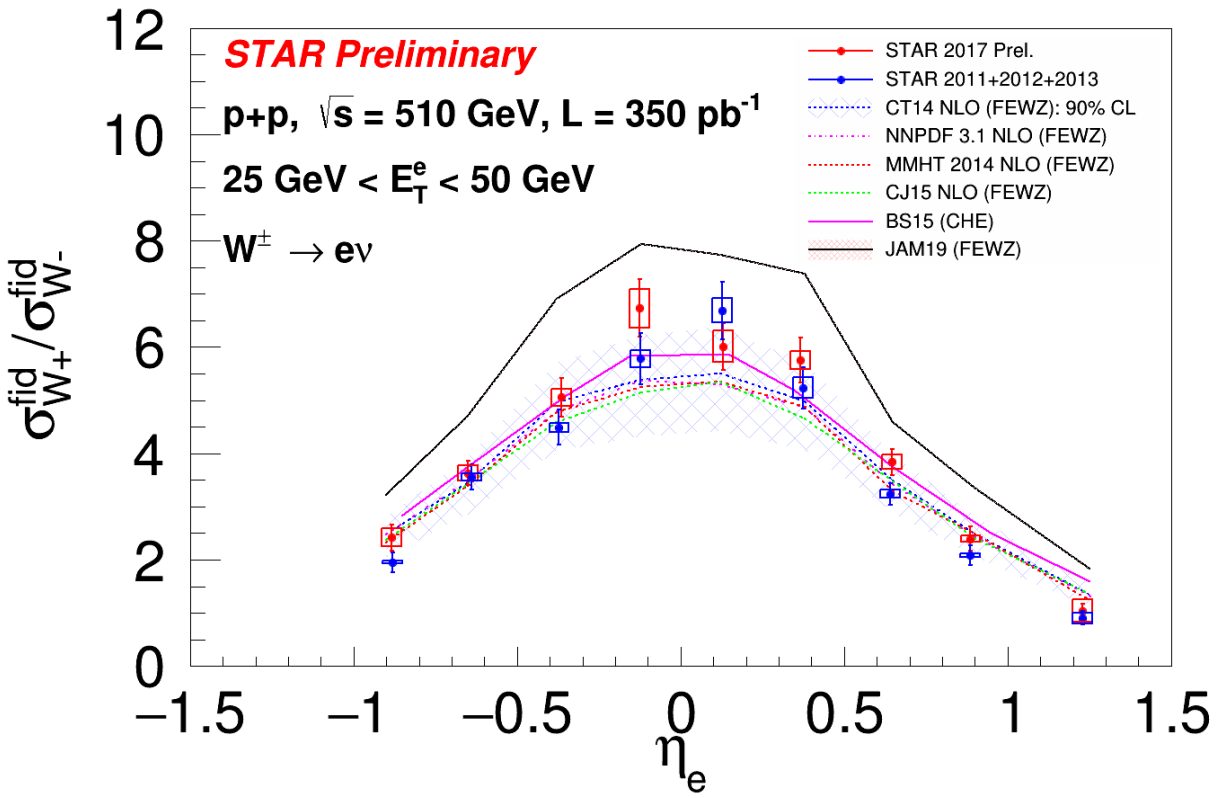




- Efficiency correction
  - Evaluates detector acceptance & efficiency of the selection process.
  - Considers e^W within $25\ GeV < E_T < 50\ GeV$.
  - Reduced efficiency in the lower η region due to detector acceptance effect.
  - The correction factor (ϵ^-/ϵ^+) is consistent with unity.
  - Remaining deviation is taken as a contribution to the systematic uncertainty.

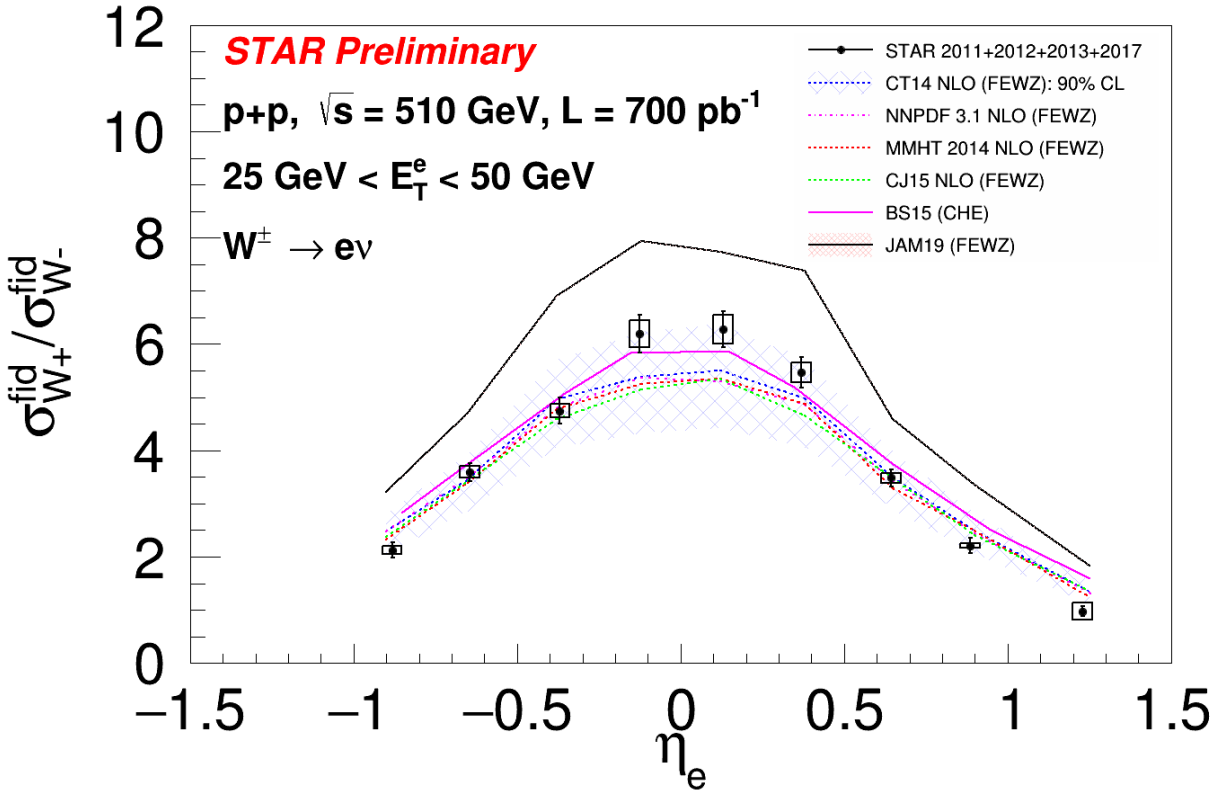
- Charge selection
  - Uses charge ($Q \times E_T/p_T$) distribution to determine the correct-charge ratio.
  - Two different fit methods used.
    - MC template method uses $W \to e\nu$ simulations for baseline description of the charge fit (nominal).
    - Log-likelihood fitting of double-gaussian function to data.
  - Difference between the two results are taken as a contribution to the systematic uncertainty.

Results



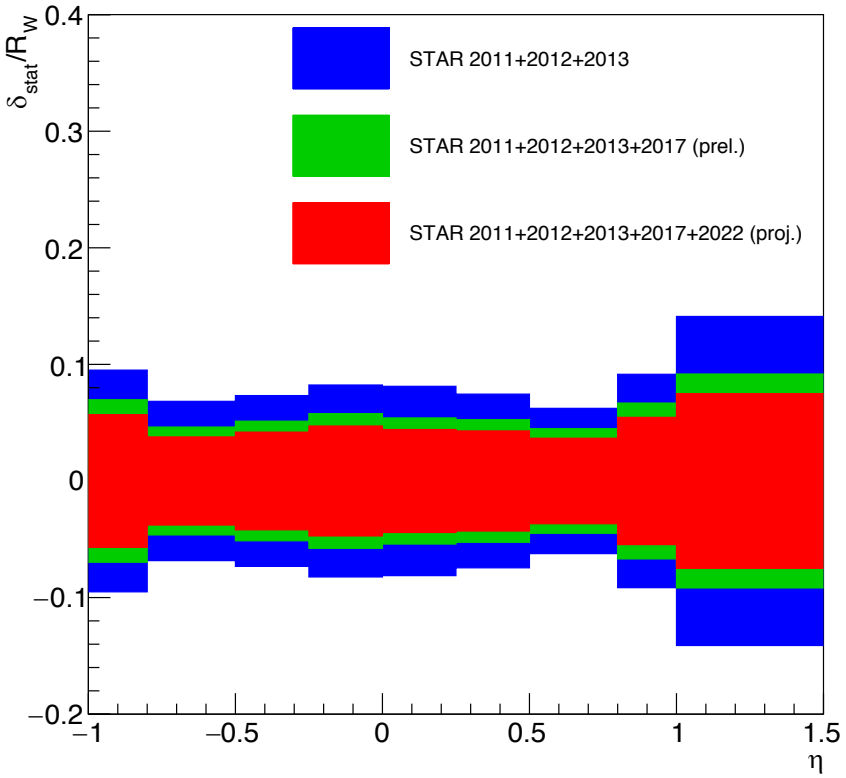
- Measurement with STAR 2011-2013 data set has been published (PRD 103 (2021) 1, 012001).
- Additional data set taken in 2017 has been analyzed and is in preliminary release.
- These measurements are consistent with each other within their uncertainties.

Results (continued)



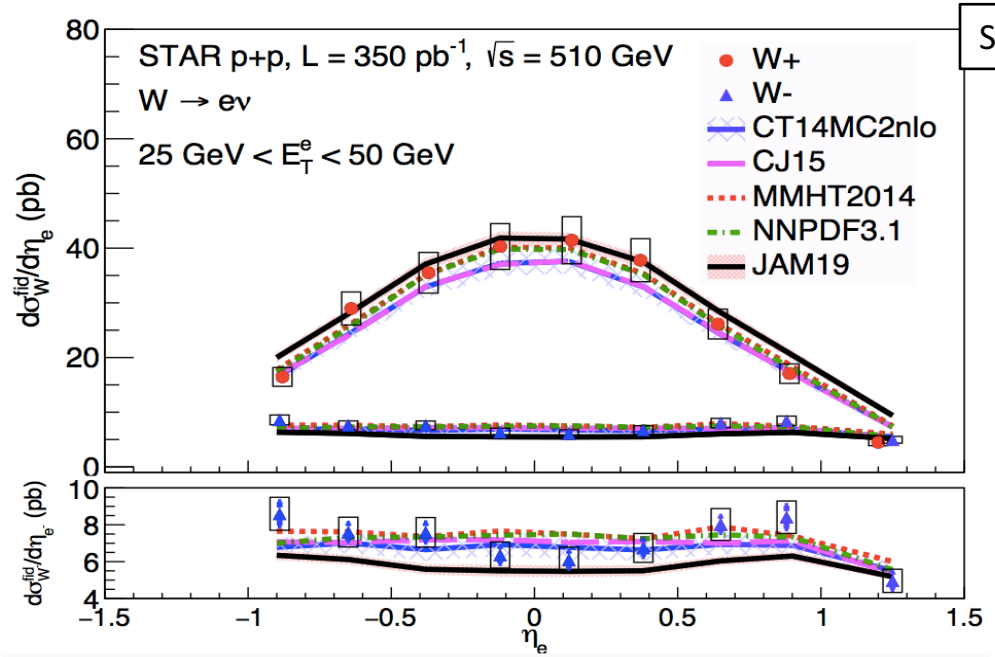
- Shown here is the result from the combined STAR 2011-2013 + 2017 data set.
  - Represents combined statistics of $L \approx 700\, pb^{-1}$.
  - Overall good agreement with the current PDF distributions.

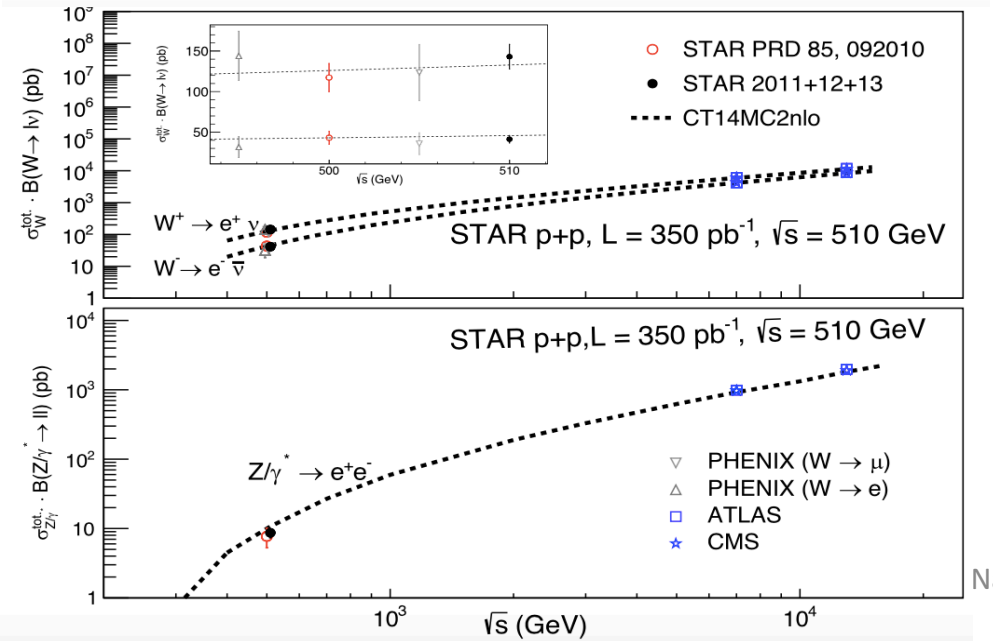
Results (projection)



- Projection for STAR 2022 data set
  - Combined statistics $\sim 1\ fb^{-1}$
  - Pushes the measurement to the systematic limit.
  - Concludes $500/510\ GeV\ pp$ program at STAR

Absolute cross sections





STAR, PRD 103 (2021) 1, 012001

- Measurement of the total cross sections.

$$\sigma_{W/Z}^{fid} = \frac{N_{sig} - N_{bg}}{\epsilon \int Ldt}$$

$$\sigma_{W/Z}^{tot} = \sigma_{W/Z}^{fid} / A_{W/Z}$$

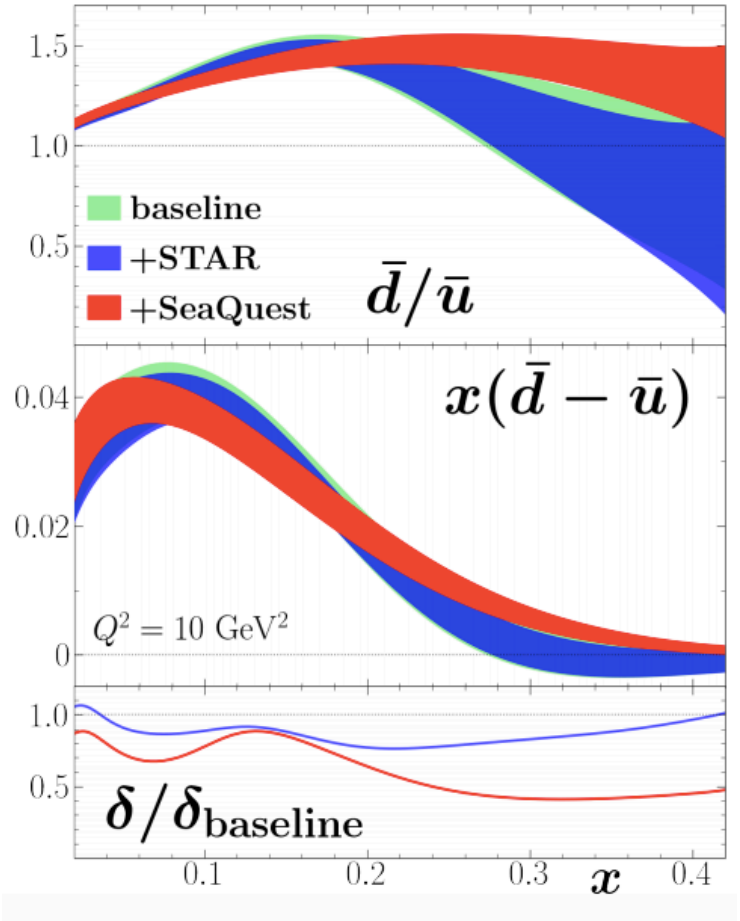
  - Acceptance correction on 2011 sample ($\sqrt{s} = 500\ GeV$) to match 2012 and 2013 samples ($\sqrt{s} = 510\ GeV$) by using FEWZ [PRD 86 (2012) 094034].

- Z reconstruction
  - The leptonically decaying $Z \to e^+e^-$ bosons are tagged by looking for electron-positron pairs.
  - Additional selection process based on the reconstructed mass M_Z to reject $\gamma^* \to e^+e^-$ processes.

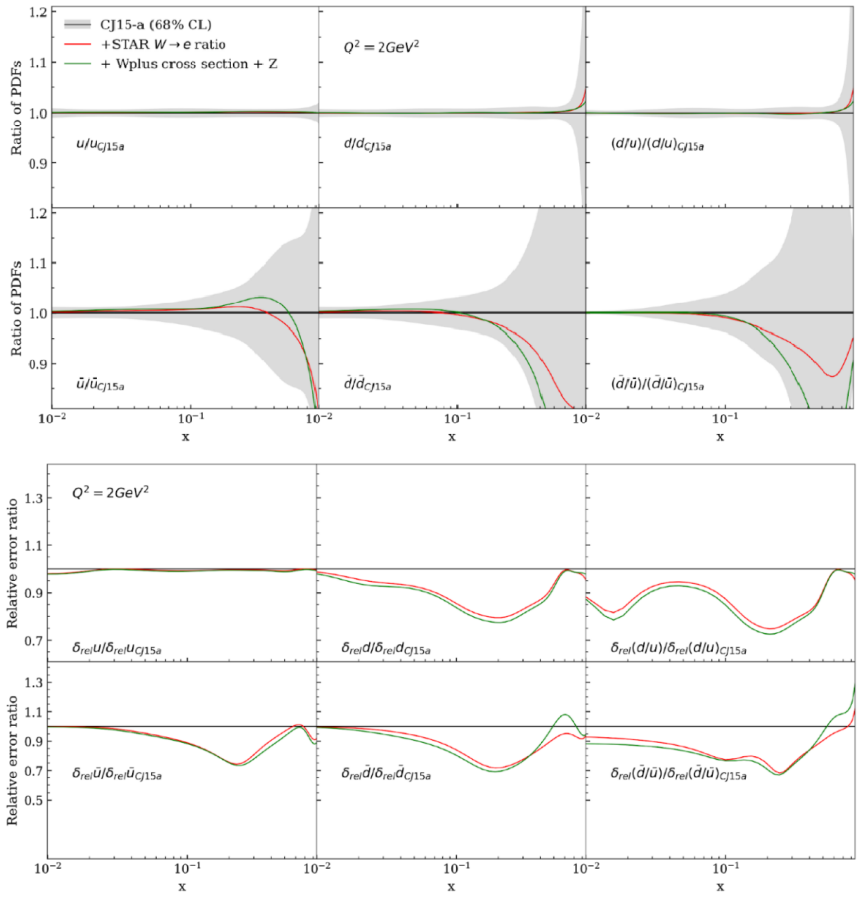
- Results with STAR 2017 in progress.

PDF impacts

JAM, PRD 104 (2021) 7, 074031



S.Park, DIS2021

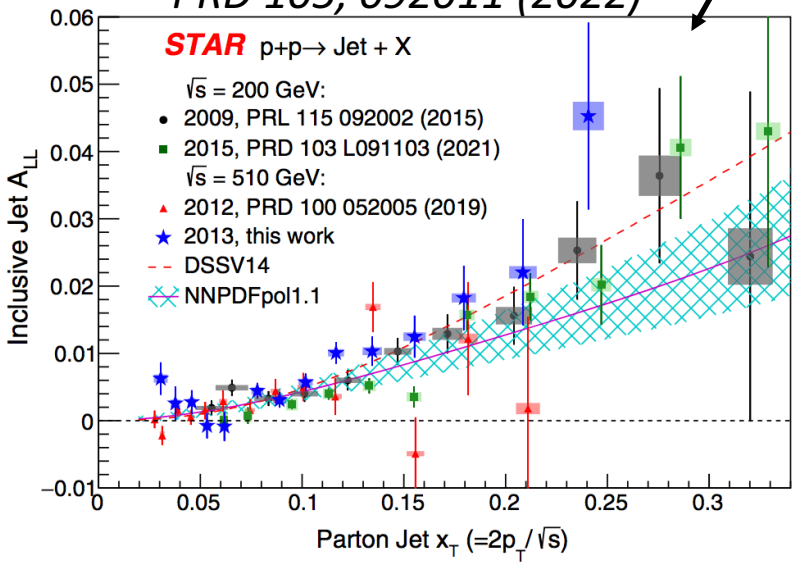


- Recent publication (STAR 2011+2012+2013) has been included in recent global fits.
- STAR data have a moderate amount of impact on the sea quark distributions around $x \sim 0.2$.

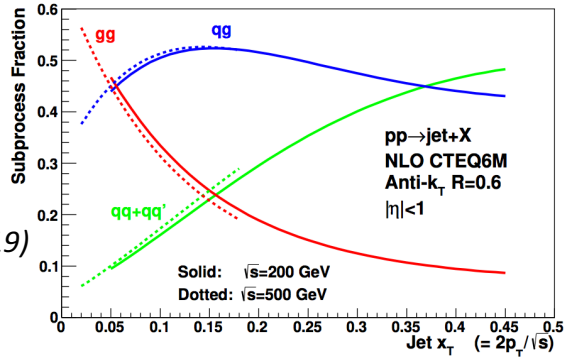
Jets at STAR

Inclusive jet A_{LL} with longitudinally-polarized pp at STAR

PRD 105, 092011 (2022)



- Inclusive jets are used at STAR to extract the gluon helicity distribution Δg via jet A_{LL} measurements.
  - $A_{LL} \sim \Delta f_1 \otimes \Delta f_2 \otimes \Delta\hat{\sigma}$
  - Two different energy modes probe different regions in x.



STAR, PRD 100 (2019) 5, 052005

Jets at STAR

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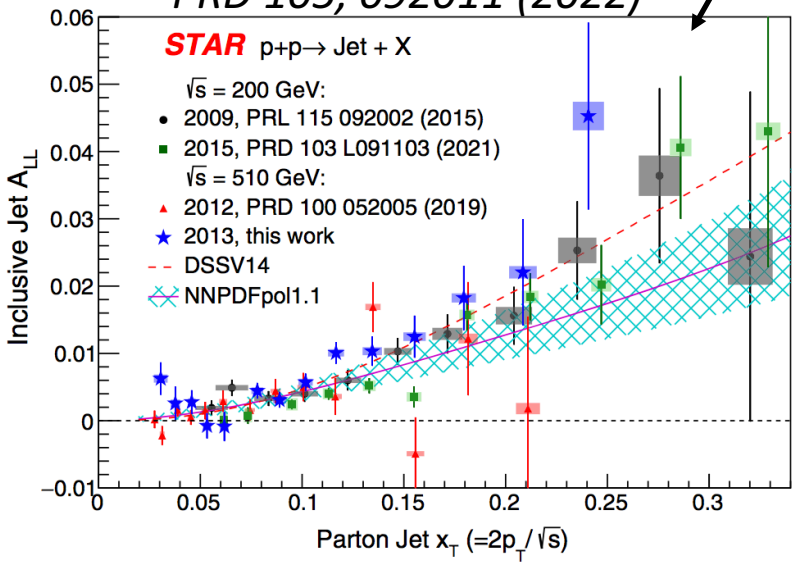
PRD 105, 092011 (2022)



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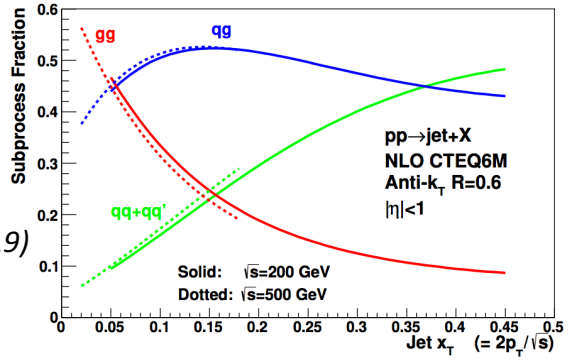
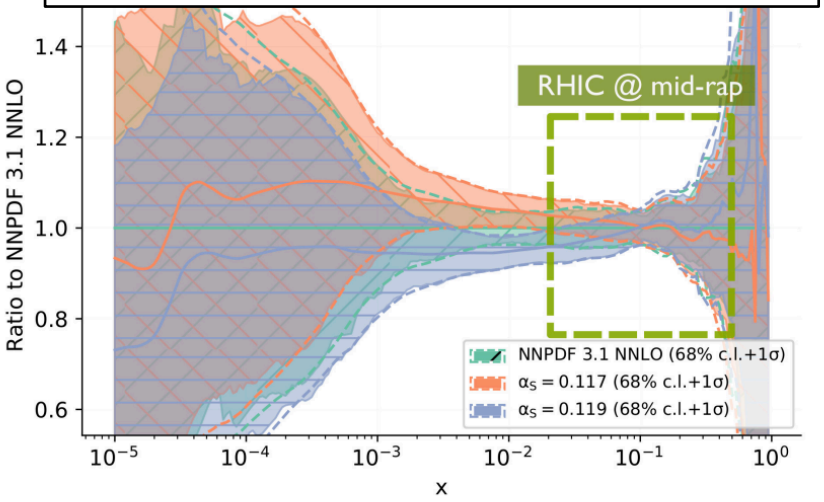


STAR, PRD 100 (2019) 5, 052005

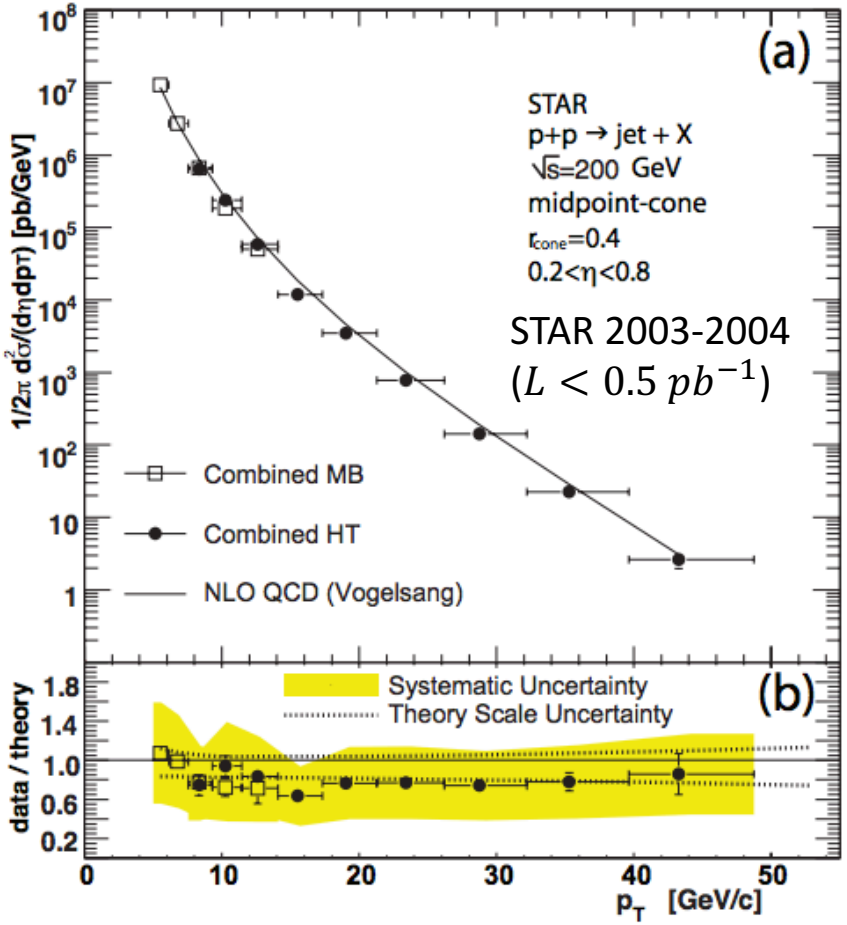
Unpolarized $g(x, Q^2)$ at $Q = 2\ GeV$



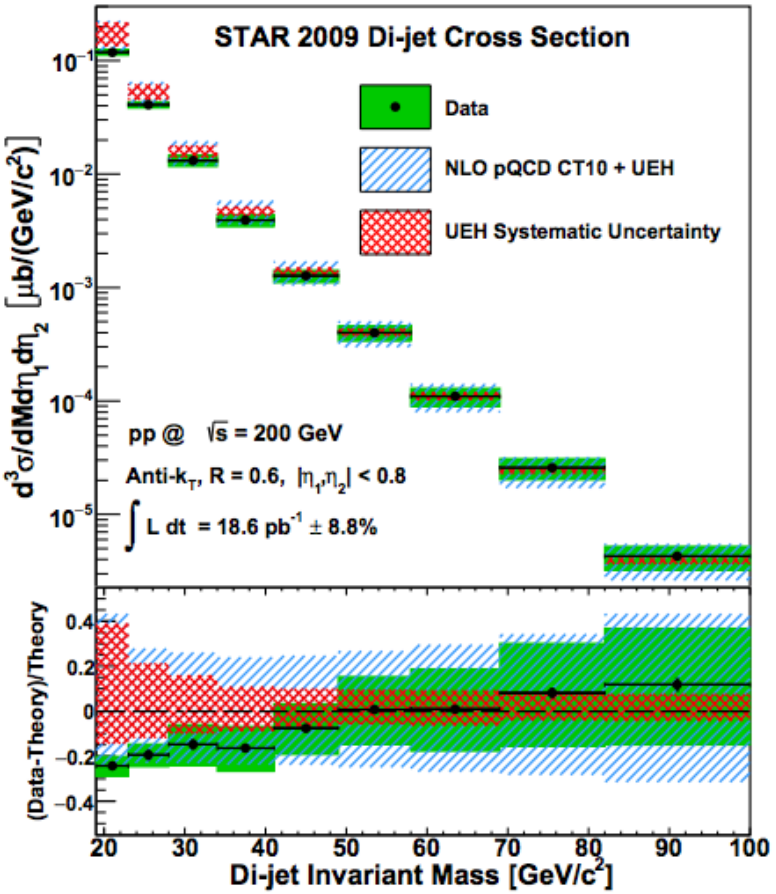
Original plot from NNPDF 3.1 Catalog of plots: α_S variations at NNLO

- Measurements of jets at STAR can be extended to the unpolarized collisions, constraining high-x behavior of gluon PDFs.
  - $d\sigma \sim f_1 \otimes f_2 \otimes d\hat{\sigma}$
  - May also serve as a normalization for other measurements, e.g., hadron fragmentation within jets.

Previous STAR measurements



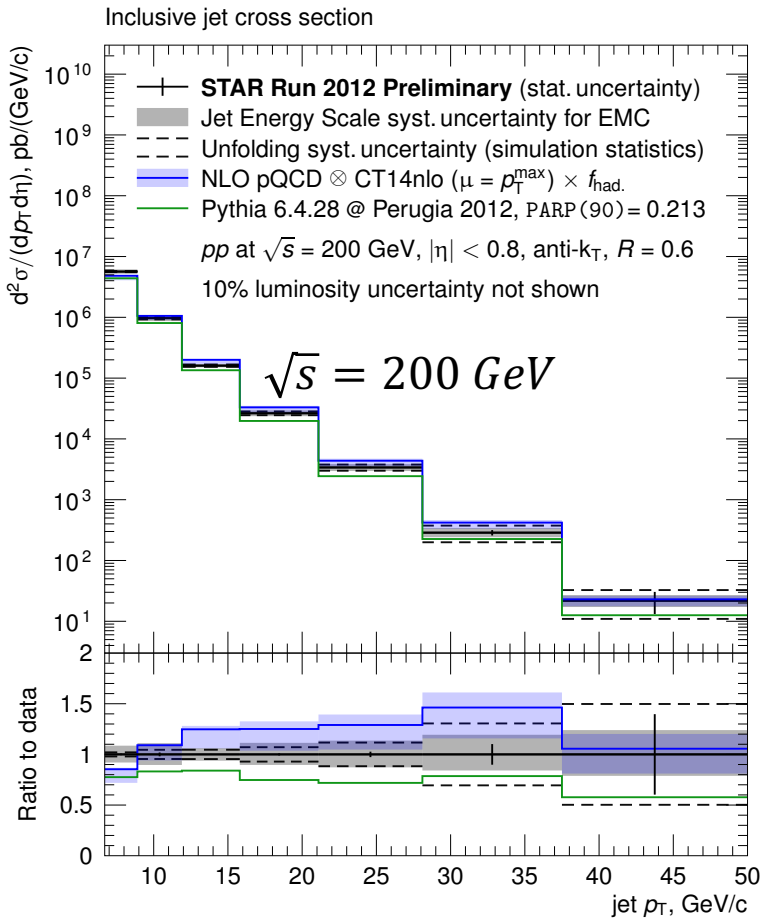
Phys. Rev. Lett. 97 (2006) 252001

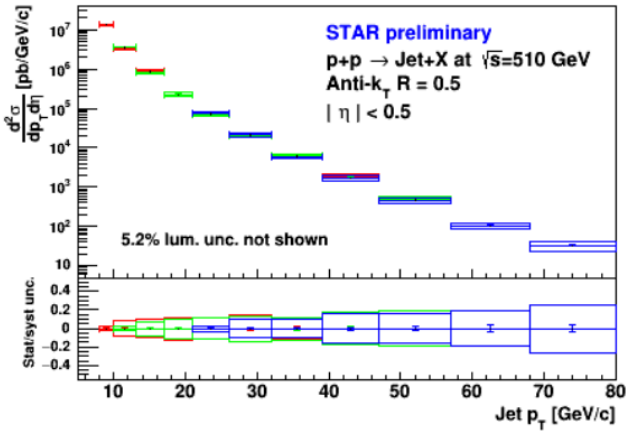


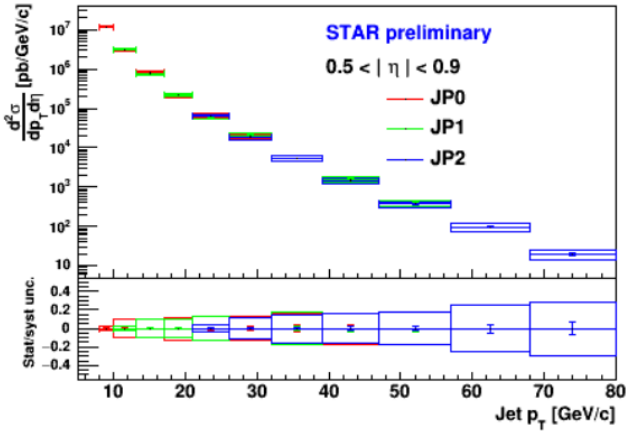
Phys Rev D 95 (2017) 071103

- Inclusive jet cross sections have been measured at STAR with pp $\sqrt{s} = 200\ GeV$ beams.
- Previous STAR measurements exist, but suffer from small statistics and high systematic uncertainty due to underlying events.

Recent measurements of Inclusive Jet







- New results feature pp $\sqrt{s} = 200\ GeV, 510\ GeV$ datasets taken from 2012, corresponding to $L \approx 20\ pb^{-1}, 40\ pb^{-1}$, respectively.
- Underlying events have been corrected for by estimating shifts in jet p_T based on the activities around the region off-axis to the jet cone.

Summary

- W^+/W^- cross-section ratio has been measured with STAR pp $\sqrt{s} = 500, 510\ GeV$ datasets.
  - Probe $\bar{d}/\bar{u}$ asymmetry in the proton sea, complementary to Drell-Yan measurements.
  - Results based on STAR 2011+2012+2013 ($L \approx 350\ pb^{-1}$) have been published.
  - STAR 2017 (adds additional $L \approx 350\ pb^{-1}$) dataset in preliminary state.
  - Combined results consistent to the current PDF distributions
  - Global fit analyses confirm constraining power in the valence region.

- Inclusive Jet cross sections have been measured with both STAR pp $\sqrt{s} = 200, 510\ GeV$ datasets.
  - Provide constraints to unpolarized gluon PDF at $0.01 < x < 0.5$.
  - Provide normalization for future fragmentation measurements at STAR.
  - Improvements made from the previous measurements due to higher statistics and reduced systematic uncertainty from underlying events.